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Double layer armor breakwater stability (case study: El Dikheila Port, Alexandria, Egypt)

Abdelazim M. Ali, Al Sayed I. Diwedar *

Hydraulics Researcher Institute, National Water Research Center, Egypt

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KEYWORDS

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Abstract This research aimed to investigate the armor layer stability of the new breakwater of El Dikheila Port. An undistorted physical hydraulic model with a scale of 1:39.73 was employed as a tool to simulate the existing and the proposed new breakwaters. The physical model was constructed in the wave basin of the Hydraulics Research Institute (HRI), Delta Barrages, Egypt. The armor layer of the new breakwater was tested with regular and random placement for the trunk and the roundhead. The damage occurs with wave height of $1.2H_s$ at the head and the trunk sections with the random placement case. The model results showed that regular placing exhibited higher stability for initial damage and gradual damage progression than the random placement of the armor units.

1. Introduction

Breakwater is an important component in port development and planning, and it protects the area in the lee side and inside the port from wave attack. This produces force on the breakwaters due to wave breaking, reflection, refraction and resulting rip currents. Usually, most of the conventional and low crested structures are composed of armor layers of different units, bedding layer of different smaller materials and toe protection consisting of armor layer units or smaller. Resulting forces on the structure affects the stability of the breakwater armor layer (including amour, toe and rear side of the breakwater). Designed breakwater should be modeled and tested to validate its functional design and to check the structure stability under the effect of the wave attack. Physical models are very useful tool to gain improved understanding of existing physical structures and processes which are currently felt to be too complex to be addressed with analytical or numerical models, and 3D larger scale structural models are commonly used for stability models.

2. Background

Design of breakwaters consists of two main stages; the first is the functional design which determines the specifications of the breakwater such as; length, height, and side slope. The second is the hydraulic design which deals with the wave condition in the protected area considering the stability level of the structure under applied forces.

Wave condition is represented in the stability formula by the significant wave height (H_s) at the toe of the structure

* Corresponding author. Mobile: +20 1008636301.
E-mail address: adiwedar@gmail.com (A.S.I. Diwedar).

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Nomenclature

T_p	peak period (s)	h	local water depth (m)
H_s	significant wave height (m)	N_d	number of displaced units/total number of units (in referenced area)
D	damage level (%)	N^3	number of displaced units (–)
N_s	stability number (–)	K_D	dimensionless stability factor (–)
Δ	relative armor density (–)	a	slope of the armor layer (–)
Fr	Froude number (–)	W	mean stone weight (ton)
D_{n50}	nominal diameter of the armor units (m)	ρ_s	density of stone (t/m^3)
N_{od}	damage number (–)	ρ_w	density of water (t/m^3)
V	mean velocity of the flow (m/s)		
g	acceleration gravity (m/s^2)		

and the peak period (T_p) which is linked to the wave steepness and the simulating forces on the structure. In addition to wave conditions, the water level plays an important role in the armor layer stability.

Breakwater stability was the focus of different studies, as Kamali and Hashim [1] through an overview study for estimating the stability of rubble mound breakwater armor layer, Shahidi and Bali [2], studied the stability of rubble mound breakwater, Benoit et al. [3], Andersen [4], and Buchem [5] focused on the conventional breakwater stability. Van Gent [6] studied the stability of the rock rubble mound breakwater with berm. The stability of the low crested structures was studied by Kramer [7], and it was argued that low crested structures (especially the head) may be more vulnerable to be damaged under slightly oblique waves. Kramer [7] claimed that the structure stability depends on the surrounding seabed, structural outer shape, characteristics of materials, and hydrodynamic parameters. It was recommended that for the stability of the armor layer, slope should be 1:2 or even gently slope.

The most important parameters affecting the structure stability are the armor units' size and the structure slope. Helgason and Burcharth [8] argued that the effect of the density is correctly described by the traditional formula for the rock armor in case of structure slope 1:2 and most likely for flatter slopes. The density is taken into consideration in Hudson [9] stability formula ($N_s = H_s/\Delta D_{n50}$), where the density is indirectly proportional to the stone size.

Armor Layer is classified based on layers to single and double armor. The stability of single and double armor layer was studied by Wolters and Van Gent [10] and Van Der Meer [11].

The armor layer placement and shape affect the stability of the structures. The impact of armor shape, porosity and placing methods was examined in different studies as Medina et al. [12] and Pardo et al. [13]. The regular placement is much effective with the frication armor units as concrete block. The random placement depending on the weight of the blocks and interlocking, is from the cost benefit is much better. Latham et al. [14] proposed a new modeling and analysis system for the concrete armor unit placement that conform to the realistic prototype structure placements.

The damage level that represents the instability has different methods for evaluation. According to Van der Meer [15], it is defined as the number of displaced units within a strip width D_n, where N_{od}, is the number of units displaced out of the armor layer/(width of tested section/(D_n)) and D_n is the side length of the concrete cube.

The structure stability is considered in the hydraulic design of the breakwater armor layer by N (stability number), and based on the experience, no damage is happening between 1 and 3. The stability number depends on the wave steepness, porosity, slope angle, wave number and the damage level. Hudson [9] in his formula considered that no damage happens when the damage level (S) is between 1 and 3, while failure occurs when $S > 10$. This depends only on the slope of the breakwater armor layer.

For the concrete block armor units, the stability is defined by the total number of moved units N_{omov} which includes both N_{od} that represents the number of the moved units out of its place toward the open sea and N_{or} which represents the units rocked in place. According to SPM [16] and Van der Meer [15], start of damage is for N_{od} of 0.5 while failure of the structure occurs with N_{od} of more than 2 for the multi-layer elements with side slope of 1:1.5.

Based on CEM [17], damage in terms of displaced units is generally given as the relative displacement, D, defined as the proportion of displaced units relative to the total number of units, or preferably, to the number of units within a specific zone around still water level (SWL).

For visual assessment of the damage degree for conventional breakwaters in physical modeling studies, it is categorized according to Losada et al. [18], in which N_d: is no damage (may be one or two loose stones start rotating), ID: is initiation of damage (a few stones start to move), IR: is Iribarren damage (big holes in the outer armor layer, but the filter layer is not visible) and D: is destruction (filter layer is exposed to direct wave attack).

Now it can be stated that stability of armor layer is the most critical issue for the breakwater stability in facing the wave attack especially the outer layer. The most important affecting factors are unit's type, weight and also the placement methods which affect very much the unit's stability. The armor units are affected by the area condition and this was taken into consideration in the hydraulic design represented by different parameters.

3. Case study

3.1. Site description

El Dikheila Port as shown in Fig. 1 is located 7 km west of Alexandria City, along the Mediterranean coast of Egypt. It

Figure 1 Location of El Dikheila Port along the Mediterranean coast of Egypt.

is a natural extent to Alexandria port due to increasing the containers movement in Alexandria port and the increasing growth of industrial development and free zones in Alexandria. El Dikheila is considered as the great hope and the dream for future expansion. The main Breakwater that protects the port from the northwest waves and has a length of 2250 m, extends from southwest to northeast and the armor layer is a double layer cubes of 26 ton weight.

3.2. Research problem

One of the main elements in the port planning is the breakwaters which are used as a protection measure against wave attack and to create safe conditions for mooring of the ships inside the port. El Dikheila Port is still suffering from high wave agitation inside the port, especially waves from northeast. The existing breakwater protects El Dikhelia port from waves coming from northwest only and fails to protect the port from northeast waves. Therefore, a new breakwater is proposed to protect the port from waves blowing from northeast. The new breakwater is designed by Delft Hydraulics, the Netherlands in 2005.

The new breakwater is located south of the main breakwater and linked to it with an angle of 67°, with the objective to enhance the wave conditions inside the port. The suggested breakwater was integrated with the 2010 master plan of the port, where the south area of the main breakwater is allocated for the development of new cargo berth.

4. Objectives

The new proposed breakwater is aiming to solve the existing problem of wave attack from the northeast and wave agitation inside the port, and the proposed breakwater design needs to be tested for stability before its construction. The main objective of this study was to investigate the stability of the armor layer of the new breakwater. The stability investigation of the proposed new breakwater includes the stability of the head and adjacent trunk sections. In addition, this research aimed to inspect the stability of the proposed breakwater armor layer units with the regular and random placement.

5. Methodology

An undistorted fixed bed 1:39.73 physical scale model was designed to test the stability of the armor layer of the trunk and the roundhead of the new breakwater of El Dikheila Port and to study the wave conditions around the breakwater and inside the port. The model scale was controlled by the available wave basin dimensions and the limitations of the wave generator and also the weight and density of the armor layer, under layer and core materials in the prototype. The model simulates part of the existing breakwater, the whole new breakwater, and part of the port. The model was constructed as shown in Fig. 2 in the coastal experimental hall of the Hydraulics Research Institute (HRI), Delta Barrages, Egypt. The evaluation is based on the designed conditions and allowable damage, in addition to available guidelines and available literature.

5.1. Model setup

The wave basin has an area of 34 m × 31 m, and maximum water depth of 0.45 m in front of the 25 m long wave generator. The wave generator consists of 96 paddles; each of 26.5 cm wide and 40 cm high and it works as one unit. The

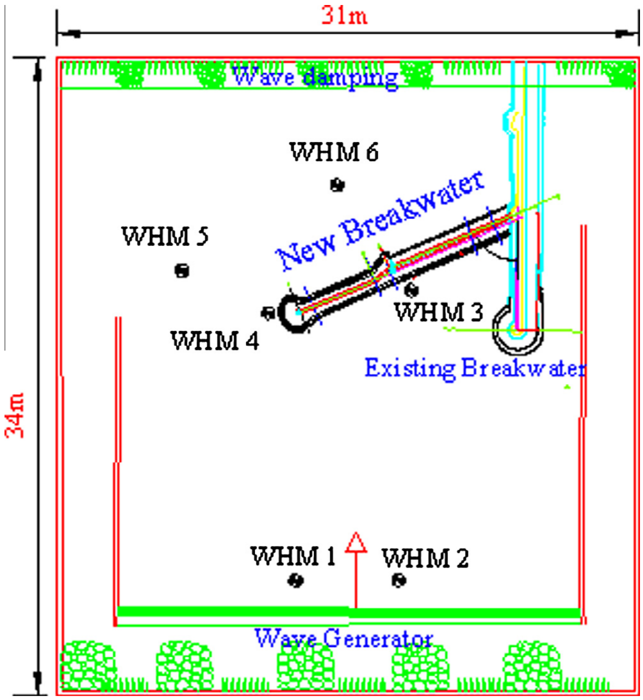


Figure 2 Physical model of the breakwater and the setup of the wave height meters.

translatory wave board is capable of generating regular/monochromatic and irregular/random waves. In the present study, JONSWAP spectrum was prescribed in the physical model operation. The online computer facilities for wave board control, data acquisition system and data processing allow for direct control and computation of relevant wave characteristics. Different measuring devices were employed for collecting the data of the experimental program, these are as follows: point gauges to adjust the water level, wave height meters (WHM), which are designed for dynamic fluid level measurements, (e.g., wave-height measurements in hydraulic models), photographs and video camera to record the cubes movements and overtopping in addition to the visual observation. The software of the wave generator has a reflection compensation system in addition to the side of wave basin in front of the wave generator have slope 1:10 to dump the waves. The overtopping was not the focus of this study, therefore it was not measured as discharge but only the impact was recorded.

Fig. 3 shows the set-up of the 3D breakwater model. The bathymetry was formed based on the survey data ensuring that the foreshore is simulating the real conditions for the area of interest. A spending beach was placed around the basin boundaries to dissipate the transmitted waves. The armor material was placed directly on the top of the under layer material of different breakwater sections. The damage was recorded by taking digital overlay photos before and after each test, and also by visual observation for determining the rocked units and counting the number of stones and cubes that were displaced more than one unit diameter (damage number N_{od}). Only after the completion of each test series (constant wave direction) the armor layer and toe were reconstructed.

The breakwater was designed based on wave height $H_s = 3.6$ m, and $T_p = 8.0$–11.5 s with return period of 50 years. The tide was simulated as an increase in water level with a maximum of 1.1 m. The armor layer was selected from the concrete blocks and based on the computational results, the armor layer weight has been selected with 6.0 t. Using this weight, the failure of the structure ($N_{od} = 2$) was computed to be occurred at $H_s = 4.5$ m. To reduce the unit's weight, the damage was selected to start at $N_{od} = 0.1$ at the designed wave height of $H_s = 3.6$ m.

For correct reproduction of the hydraulic phenomena in the physical model, a complete similarity including geometric and dynamic similarity between prototype and model breakwater was fulfilled. The Froude similarity model was adopted in the physical model because both inertia and gravitational forces are dominant. It means that the Froude number in both physical model and prototype must be identical based on the following equation:

$$F_r = \frac{v}{\sqrt{gh}} \tag{1}$$

where Fr is the Froude number, υ is the average flow velocity (m/s), h represents local characteristic water depth (m) and g is the acceleration of gravity (m/s^2). This resulted in a physical model with the scale of 1:39.73 ($\lambda = 39.73$). Also the mass scale was corrected due to the differences between water densities in prototype and model by applying Hudson's stability formula and Van der Meer [15]:

$$N_s = H_s/\Delta D_{n50} \tag{2}$$

Figure 3 Model construction.

where N_s is the stability number, H_s is the significant wave height, Δ is the relative armor density, and D_{n50} is the nominal diameter of the armor units.

$$N^3 = K_D \cdot a \frac{\rho_s H_s^3}{W\left(\frac{\rho_s}{\rho_w}\right)} \tag{3}$$

For accurate modeling, the ratio between the inertia and gravity forces should be the same in reality and model. Consequently, the weight and the dimensions of the armor layer, under layer and core materials were defined. The data of the armor layer, under layer and core materials in prototype and for the model are listed in Table 1.

6. Experimental work

In breakwater stability studies, the damage is determined in zones or selected areas, so it was necessary to divide the breakwater into zones and for each zone the original number of armor layer was identified, Fig. 4. The significant wave height (H_s) for this study is 3.6 m. The model test program as illustrated in Table 2, was designed to investigate the armor layer stability under different wave conditions varying between 40%, 60%, 80%, 120% and 150% of the significant wave height (H_s) at deep water, which is based on the previous studies and recommendations of Delft Hydraulics for stability models. The peak wave period T_p was calculated for each wave condition. Also, the breakwater was tested with mean seawater level (MSWL) and with 1.1 m + msl.

7. Results

The damage of the armor layer was recorded for each test run and the percentage damage was then calculated based on the number of cubes that moved or rocked in place. For the bedding and the toe layers, the percentage of damage was estimated due to the difficulties of defining the number of stones that moved from its place. In this study, damage is defined based on the CEM [17] as N_d (the number of displaced units/total number of units in referenced area). The displaced units are defined as the units that moved more than its D_n. The breakwater was exposed to different wave conditions simulating calm, design and storm conditions, two cases of armor layer placing were investigated, and in all cases the regular placement was found to be more stable as shown in Figs. 5 and 6.

It was found also that in the case of increasing the water level, the damage level increases with the two types of unit's placement. Figs. 7–10 illustrate the progression of the damage and the damage level of different breakwater sections with regular and random placement. It illustrates that the stability of the armor layer of the breakwater is much higher than the designed. The stability of the head section was much less than the other sections with wave height more than the designed. For the head section, the damage level of the armor units is higher in the case of random placement. In the case of the random placement; increasing the water level results in higher damage level. Both the toe and bedding layers were stable for the different wave conditions and the different placing techniques.

In this study, the initial damage occurred at a stability number ($N_s = H_s/\Delta D_{n50}$) of 2.3. This result agrees with CEM [17] for the case of random placement of double layer armor with cube units. They determine the stability number N_s = 1.8–2 for the damage level of D = 0%, and stability number N_s = 2.3–2.6 results in moderate damage of D = 4%, which is the case for the head section with random placing.

The damage was found to take place when the breakwater is exposed to wave storm of 120% of H_s, for both the head and the trunk sections (zones 1, 2, and 3). The head section is the least stable section especially under the random placement where the damage starts the progression at the designed wave height with damage level of 2%. This result agrees with the previous studies, that the head of the breakwater is much vulnerable due to the curvature and it is the least stable part especially in the case of emerged breakwaters, as shown in Vidal et al. [19], Van der Meer [20], where the interlocking is much less than other parts. It was recognized that at wave height of 5.4 m, there is a severe damage level of 5.47%. Zone 4 was found to be more stable under different placement techniques with damage level of 1.4% under wave height of 4.3 m and N_{od} of 0.05 in the random placement case, as it is located in the sheltered area of the existing breakwater.

In General, the present study results agree with the previous studies and literature, where it was found that the actual stability

Table 1 Breakwater characteristics.

Breakwater dimension	Prototype	Model
Crest level (first 300 m)	6.5 m + msl	6.5 m + msl
Crest level (last 250 m)	1.5 m + msl	1.5 m + msl
Crest width	Varies from 5.5 m to 11 m	0.14–0.28 m
Free board	Varies from 1.2 m to 6.2 m	0.03–0.16 m
Berm width	3.0 m	0.076
Side slope (head sec.)	1:2	1:2
Side slope (other sec.)	1:1.5	1:1.5

Breakwater layers	Prototype		Model	
	Weight (ton)	Density (t/m^3)	Weight (g)	Density (t/m^3)
Armor (cube units)	6	2.35	320	1.69
Underlayer (stones)	0.5–1.5	2.6	14.5–43.5	2.2
Core (stones)	0.01–0.06	2.2	0.29–1.7	2.2
Seawater		1.03		1.0

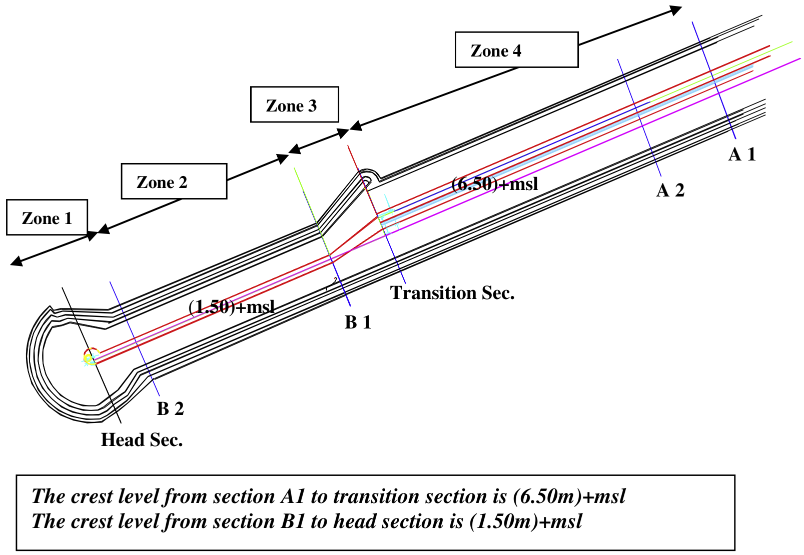


Figure 4 Breakwater zones.

Table 2 Model test program.

Test number	Test condition		Sig. wave height at deep water, H_s (m)	Peak period, T_p (s) $T_p = 4.5\sqrt{H_s}$
	Seawater level (m) + msl	Wave height, H_s (%)		
1	0.0	40	1.45	5.42
2	0.0	60	2.15	6.60
3	0.0	80	2.90	7.70
4	0.0	100	3.60	8.50
5	1.1	100	3.60	8.50
6	0.0	120	4.30	9.30
7	1.1	120	4.30	9.30
8	0.0	150	5.40	10.5

Figure 5 Stability of armor layer after test 7 (regular placement, head section).

Figure 6 Stability of armor layer after test 15 (random placement, head section).

is usually much higher than the designed one, as shown in Van der Meer [20], and still there is a disagreement between the measured stability numbers and predicted, Kim and Park [21].

The prototype conditions during the performed tests are very crucial; consequently wave profiles were recorded continuously during these tests in order to obtain reflected and incident waves. This was done for all tests by using Wave height meters distributed, in the deep water in front of the wave maker and around the breakwater as in Fig. 2. It was found that the new designed breakwater succeeded to reduce the incident waves in the lee side by 50% for WHM6 compared to the wave height in front of the breakwater at WHM3 in the extreme events of H_s = 4.3 m, and by 55% for WHM5.

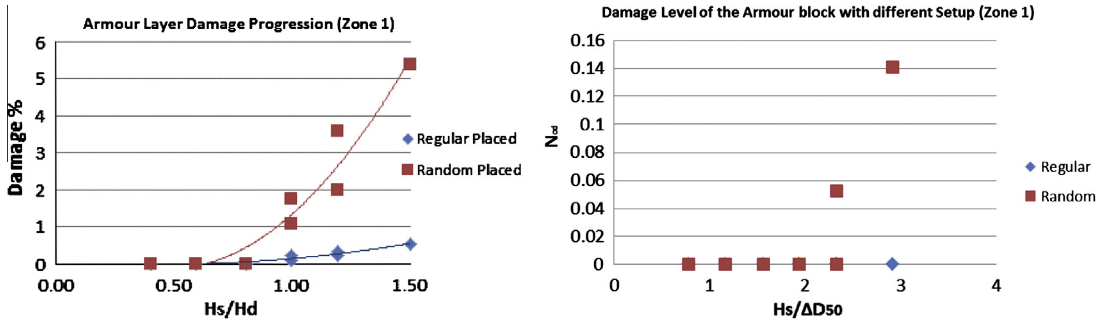


Figure 7 Damage progression and damage level of the head section.

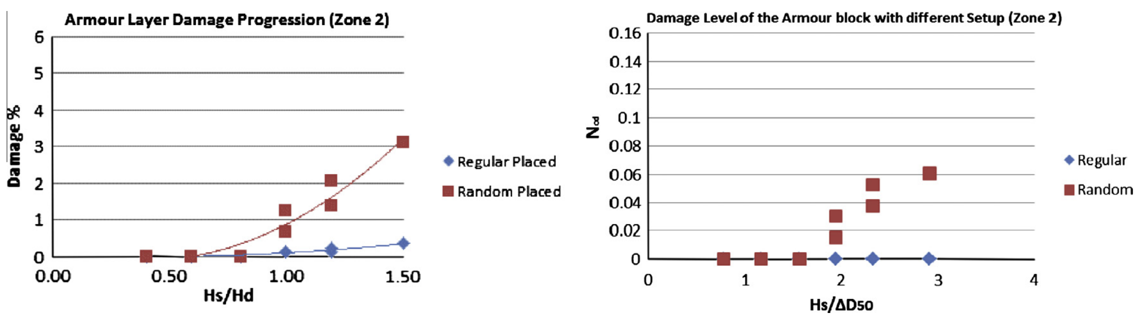


Figure 8 Damage progression and damage level of zone 2.

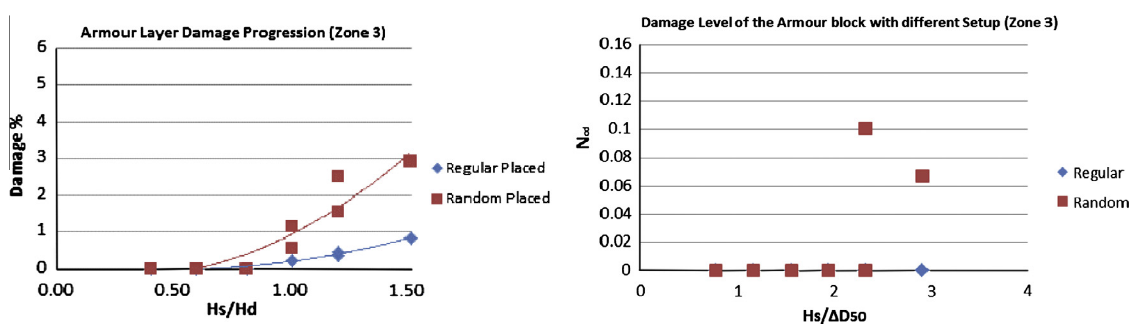


Figure 9 Damage progression and damage level of zone 3.

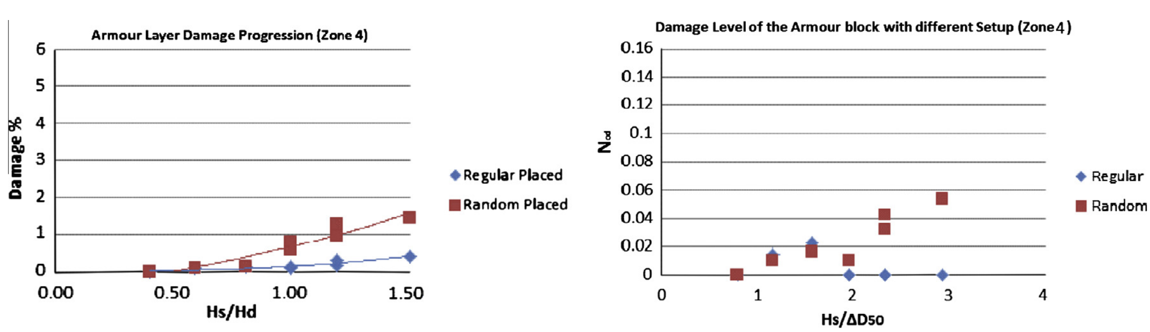
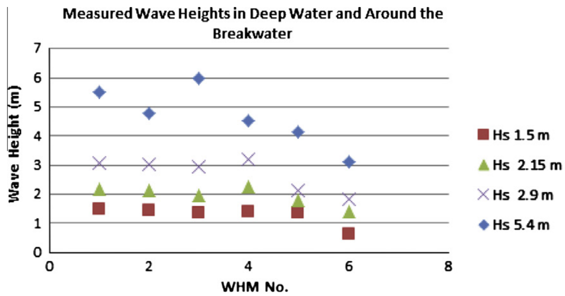


Figure 10 Damage progression and damage level of zone 4.

The obtained results showed that for WHM5 and 6 with H_s of 4.3 m and water level condition, the reduction in the incident wave height is approximately 70% and 80% respectively. The overtopping was increased with wave heights more than the designed wave heights and with high water level. Fig. 11 shows the measured wave heights at different locations for the different test conditions.



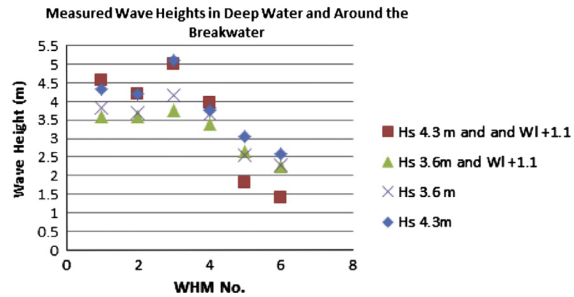


Figure 11 Incident wave height under different test conditions.

8. Conclusions and recommendations

8.1. Conclusion

Based on the study results, the following conclusions may be drawn out:

- The breakwater is stable under extreme wave attack. The observed damage to breakwaters armor layer is lower than the designed one and therefore the stability factor is much higher than the designed.
- Regular placing exhibited higher stability for initial damage and gradual damage progression rather than the random placement of the armor units. For the random placing technique, damage does not progress until a critical wave height or damage is attained. For the regular placed cubes, the breakwater is highly stable, while with random placement, the head section is exposed to damage in storm conditions.
- The breakwater succeeded to reduce the wave height at the lee side, with minimum reduction percent of about 27% and maximum of 70% of H_s under the tested different wave conditions.
- The armor layer damage may occur if design wave conditions are exceeded or the structure is exposed to repeated storms adjacent to the design conditions.

8.2. Recommendations

- Based on the detailed analysis of the breakwater reaction to the wave attack, it is recommended to use the regular placement method of armor units, as the actual stability is much higher than the random one, and the damage progression is gradually occur.
- It is also recommended to increase the weight of the armor layer units for zones 1 and 2 from 6 tons to 9 tons in order to assure the stability of the armor layer with random placement.
- From the study observations, it is recommended to raise the crest level for zones 1 and 2 from 1.5 m + msl to 4.0 m + msl in order to reduce the overtopping which may affect the stability of the rear armor units.

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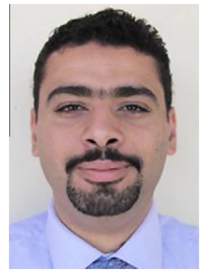
Abdelazim Mohamed Ali is an associate professor at the Hydraulics Research Institute (HRI), National Water Research Center (NWRC), Delta Barrage, Egypt since 1989. He accomplished his undergraduate study in Civil Engineering, Faculty of Engineering, ZAGAZIG University in 1987. In 1998 he completed his M.Sc. degree from UNESCO-IHE, Delft, the Netherlands, in the field of Coastal and Port Development. In 2005, he obtained his Ph.D. degree in Civil Engineering from Cairo University, with specialization in Hydraulic Engineering. His basic experience is in river and hydraulic engineering with wide experience in both fields river and coastal engineering by using physical and mathematical modeling techniques.



Al Sayed Ibrahim Diwedar is working as a researcher for the Hydraulics Research Institute (HRI) since 2002. He accomplished his undergraduate study in Civil Engineering, Shoubra Faculty of Engineering, ZAGAZIG University – BANHA BRANCH in 2002. In 2005 he completed his M.Sc. degree from UNESCO-IHE, Delft, the Netherlands, under the Water Science Department, specialized in Coastal and Port Development. In 2009, he obtained his Ph.D. degree in Civil Engineering from Ain-Shams University, with specialization in Coastal Engineering Protection. His basic experience is in river and hydraulic engineering with wide experience in modeling and hydrographic survey. His main specialization and experience is coastal engineering, with the main interest in wetlands and coastal zone management. He started his professional career in HRI as an executive engineer of physical and mathematical models, then as a project engineer, after that he joined the survey department at HRI and worked as a team leader in different survey missions.